Fuel-Efficient Platooning in Mixed Traffic Highway Environments

Jeffrey Rupp, Principal Investigator

American Center for Mobility (ACM)

June 2, 2020

2020 DOE Vehicle Technologies Office

Annual Merit Review – Project ID: TI103

American Center for Mobility
CONNECTED. AUTOMATED. VALIDATED.

Overview

Timeline

- Start: October 1, 2018
- End: December 31, 2020*
  - ~ 40% complete (testing & demo basis)
  - ~ 75% complete (calendar basis)

Budget

• Total	$4,922,146
• DOE	$2,447,271
• 50% Cost Share	$2,474,875
• BP1: 2019	$2,416,226
• BP2: 2020	$2,505,920

Premise

- Platooning, or ‘drafting’ / ‘tailgating’, improves fuel economy by reducing aerodynamic drag
- There’s an ideal gap (headway) between vehicles for maximum improvement

Barriers

- Real world complexity impedes:
  - Maximizing fuel economy – technical challenge of maintaining optimal headway alongside traffic, weather, and roads that aren’t level or straight
- Public safety precludes:
  - Operating vehicles at close headways – risk from testing and operating unproven control systems in the needed complexity of real-world environments

Partners

- American Center for Mobility
- Auburn University
- University of Michigan-Dearborn
- Michigan Department of Transportation (MDOT)
- U.S. Army Combat Capability Development Center, Ground Vehicle Systems Center
- National Renewable Energy Laboratory

*Excluding COVID-19 extension

Project Objectives

Objectives

- Develop vehicle automation* for reduced headway that adapts to:
  - Traffic (gap for cut-ins)
  - Road curvature (vertical and lateral)
  - Bridges and Tunnels
  - Weather (vehicle dynamics & communications)
- Conduct testing with increasing complexity in four phases:
  - Simulation
  - Baseline – NCAT** (2 phases)
  - Advanced – ACM (2 phases)
  - Public – MDOT-hosted demo

Impact on Barriers

- Automation negates the challenge of complexity, precision, and response time that humans can't ensure when driving with reduced headway
- Develop proven technology without undue risk to the public

VTO Integration Goals

- Affordability
  - Cost savings from increased energy efficiency
- Economic growth (from automation):
  - Increase trucking capacity
  - Reduce shortfall of drivers in the trucking industry
- Reliability/Resiliency
  - Safely platooning in public (testing & deployment)

**Automation includes localization, vehicle control, and vehicle-to-vehicle (V2V) communication*
***National Center for Asphalt Technology (NCAT), Auburn, AL*

Approach

1. Test vehicles in varying automated platoon configurations
2. Measure fuel consumption
3. Increase the complexity of driving scenarios

Vehicle & Powertrain Diversity:

Peterbilt – Commercial (2x)

- A1 – PACCAR MX13-320V engine
- A2 - Cummins ISX15 415 ST2 engine

Daimler Freightliner – Military M915A5 (2x)

- Diesel Series 60 engines (both)
- T13 (heavily armored)
- T14

Trailers – unloaded

Platooning Diversity:

- Running order, e.g.: place heaviest truck 2nd, 3rd, or 4^{th} in formation
- Headway distance: 35, 50, 75, 100 ft.

Approach

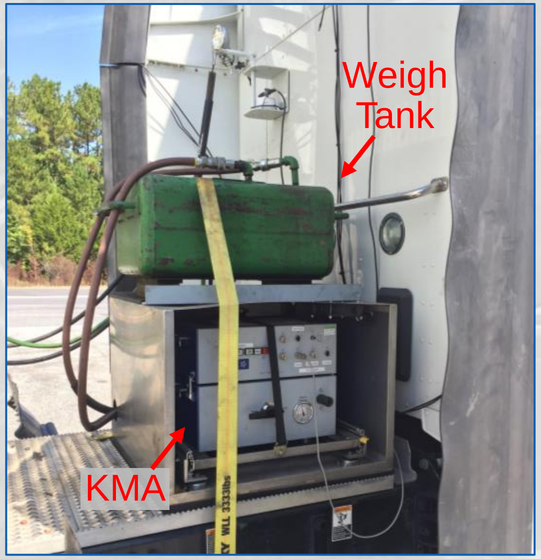
1. Test vehicles in varying automated platoon configurations
2. Measure fuel consumption
3. Increase the complexity of driving scenarios

Vehicle Automation

- By-wire control of throttle and brakes
- Auburn's Dynamic-Base Real Time Kinetic (DRTK) position data utilizes dual frequency antennas and Novatel flex packs on each vehicle to obtain differential GPS position estimates with a 2cm accuracy.
- Vehicle-to-Vehicle (V2V) communication using Dedicated Short Range Communication (DSRC) Wi-Fi protocol
- Radar – electronically scanned radar with long-range narrow field of view and short-range wide field of view
- Control software

Approach

1. Test vehicles in varying automated platoon configurations
2. Measure fuel consumption
3. Increase the complexity of driving scenarios



Parallel Approaches:

- **Weigh tanks** – record fuel (weight) consumed when covering 40+ miles at 45 mph, isolated to just the test period (In the spirit of SAE J1321 Type II; driving only, not key-on to key-off)
- **CAN** – Commanded fuel rate recorded from the vehicle's powertrain Controller Area Network (CAN)
- **KMA** – Fuel flowrate measured via AVL KMA Mobile™ flow meter for transient events (e.g. vehicle cut-in / merge with platoon formation)

Approach

1. Test vehicles in varying automated platoon configurations
2. Measure fuel consumption
3. Increase the complexity of driving scenarios

Baseline:

- Level ground (+0.5%, -0.5%)
- 490’ R corners
- Uniformity supports repeatability

Simulation – “What If?”

- Control system performance
- Sensor performance (incl. weather)

Advanced:

- Uphill, downhill (6x; +4.3% max, -3.6% min)
- Overpasses, underpass, tunnel, merges
- Transients & irregularity provide real world challenges

Public:

- TBD highway

Milestones

1. Test vehicles in varying automated platoon configurations
2. Measure fuel consumption
3. Increase the complexity of driving scenarios

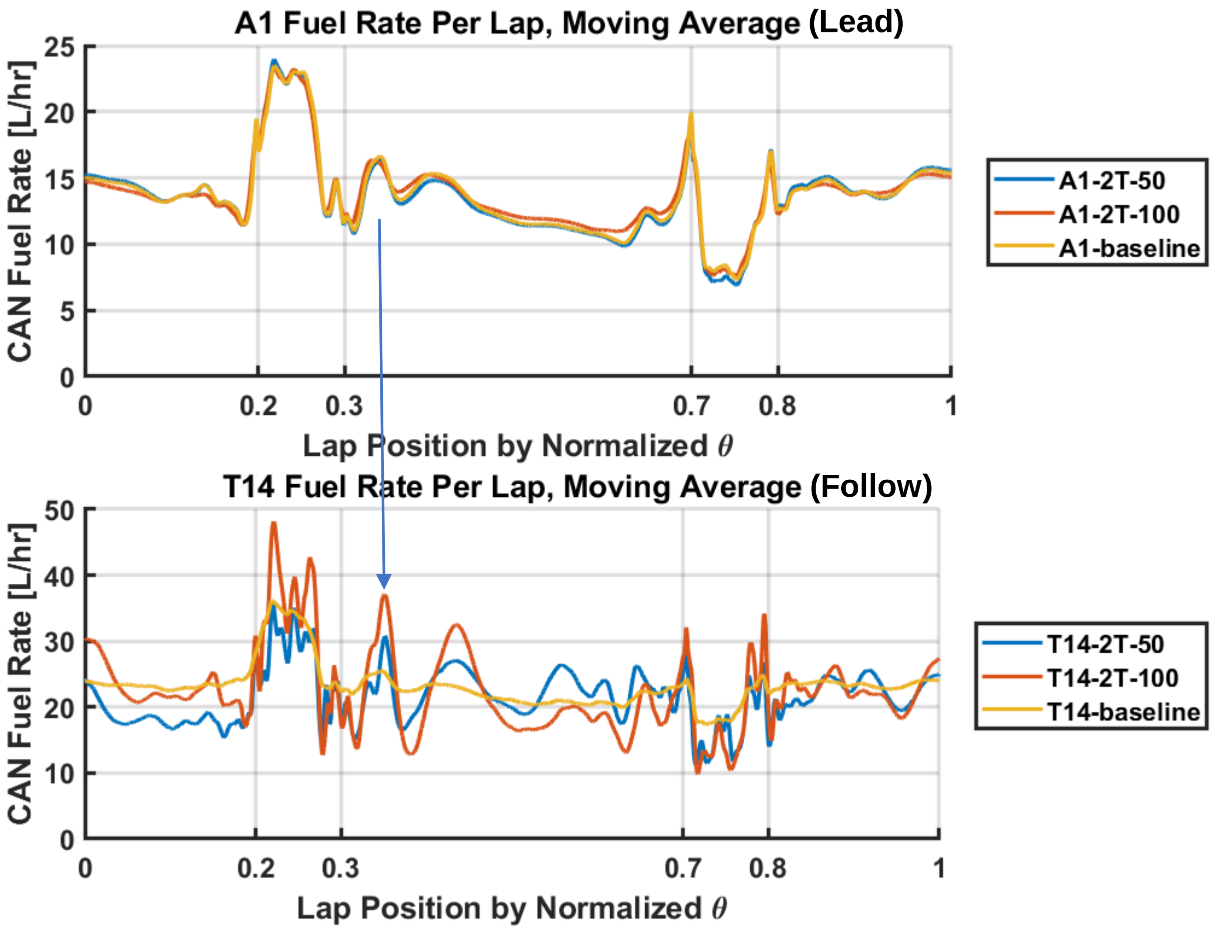
Milestones	Budget Period 1 (BP1)					BP2			
	2018	2019				2020			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
(Vehicle instrumentation updated)	Task 1.1								
Design of experiments - key parameters set for simulation, design, risk reduction	1.2								
Simulations developed; "What if" testing conducted	1.3								
Baseline & Advanced testing complete - algorithms & communications (phase 1)			1.2						
Initial performance assessment complete			1.4						
Four-truck platoon testing complete (Go/No Go)				1.2					
(Develop modified algorithms)						2.1			
Simulations updated						2.3			
Baseline & Advanced track testing complete (phase 2)							2.1		
Data collection and analysis							2.4		
Final demonstration complete - Michigan public roads								2.2	

Google Earth

Example Fuel Consumption Testing

Lap-Averaged Fuel Analysis

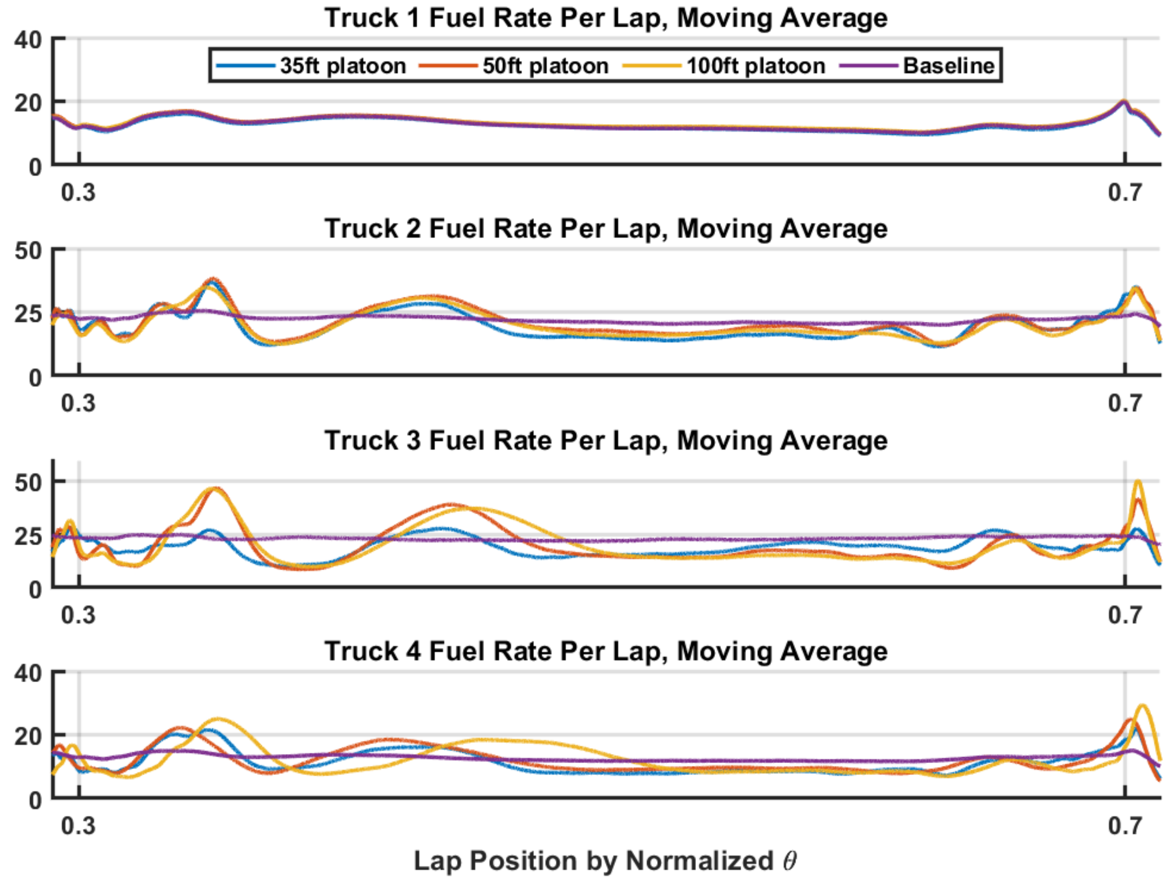
- CAN Fuel Rate
- Propagation of disturbances
  - Baseline vs. platooning fuel consumption profile
  - Lead cruise control influences followers significantly



Example Fuel Consumption Testing

Lap-Averaged Fuel Analysis

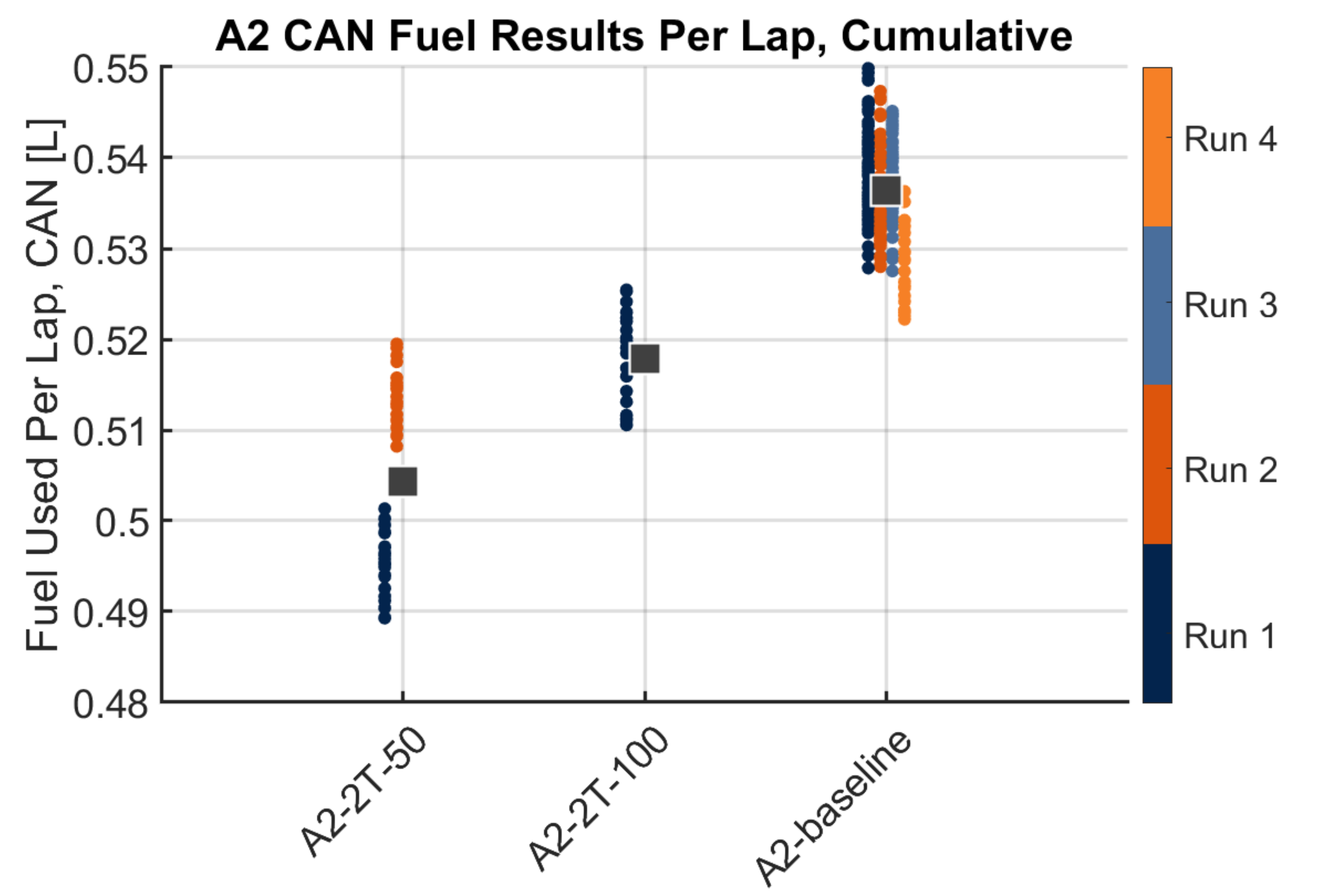
- Fuel commands compound in platoon
- This compounding fuel rate indicates potential for optimization
- Increased headway results in increased delay



Example Fuel Consumption Testing

Data By Lap

- Average fuel consumption per lap
  - 1 (baseline), 2, and 4 trucks
  - Headway: 35, 50, 100
- Each datapoint represents a lap of fuel consumption

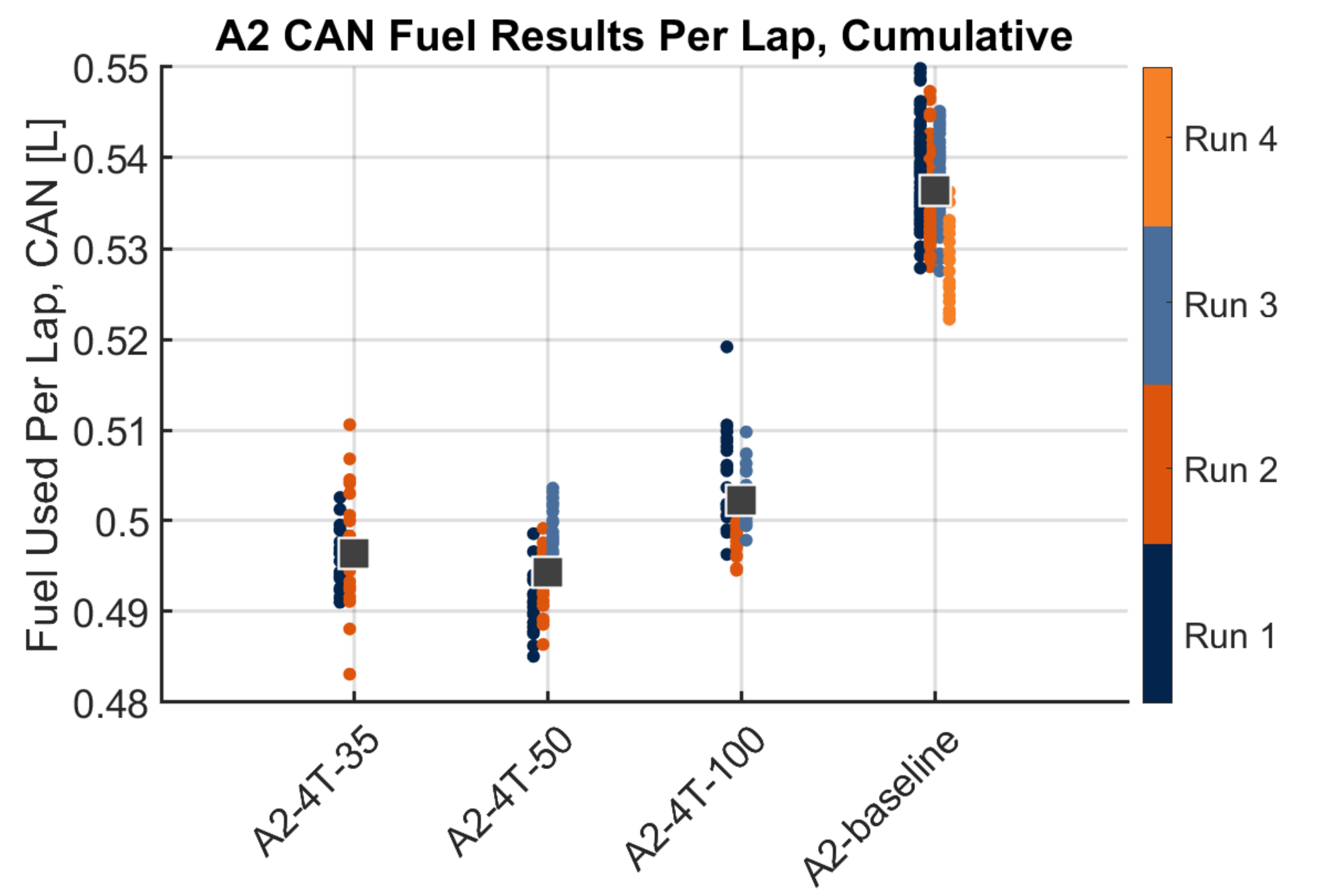


Project Progress & Accomplishments:

Example Fuel Consumption Testing

Data By Lap

- Average fuel consumption per lap
  - 1 (baseline), 2, and 4 trucks
  - Headway: 35, 50, 100
- Each datapoint represents a lap of fuel consumption



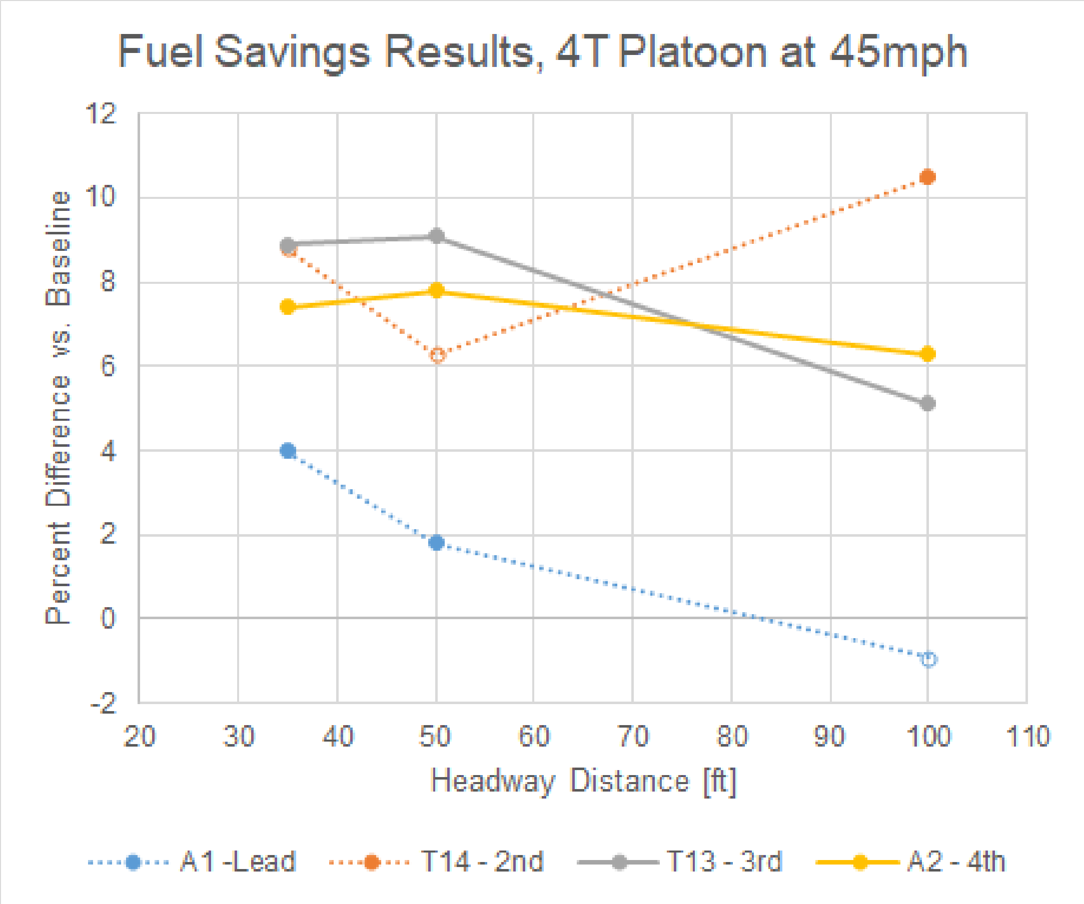
Project Progress & Accomplishments:

Example Fuel Consumption Testing

Reduction in consumed fuel during 4-truck platooning at various headway (following) distances:

- 5-10% for following vehicles
- 0-4% for the leading vehicle

(Subject to variables: vehicle speeds, truck masses, trailer loading, grades, curve radii, engine fan on-time, instrumentation stability, transient events obviating use of a control truck, diverse powertrain efficiencies, driver offset in lane, ambient winds, grades, weights, vehicle speed, engine fan on-time, etc.)



Example Sensor System Challenges

- Blocked GPS performance
- Radar signal multi-path
- Radio signal multi-path

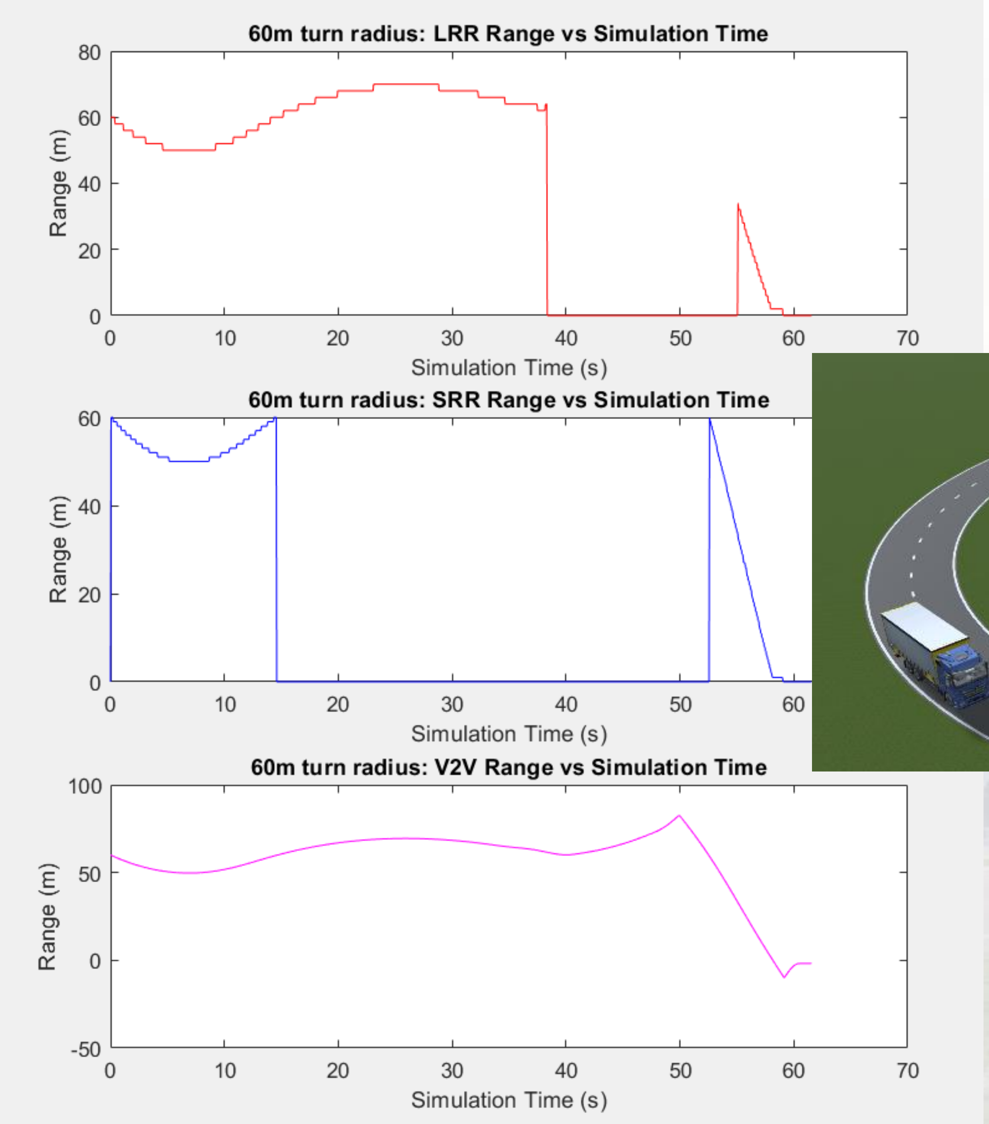
Simulation – Impact of Road Curvature

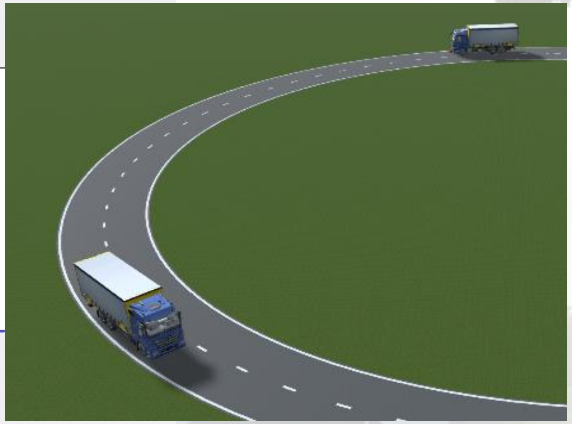
What If?

- Radius of the road curvature < 200’
- Follower headway = 150’

Performance

- Neither short- or long-range radar detects leader
- Platooning control relies on vehicle-to-vehicle (V2V) communication





Project Progress & Accomplishments:

Radio Requirements

Key Performance Indicator (KPI)	Test Criteria	Target	Observations
Received Signal Strength Indicator (RSSI)	Signal Strength	Greater than -90 dBm	Avg. -66 dBm
Packet Latency	Transmission Time	Less than 10 ms	Avg. ~2.5 ms
Network Utilization	Fraction of Network Capacity In Use	< 10%	Avg. ~3-5%

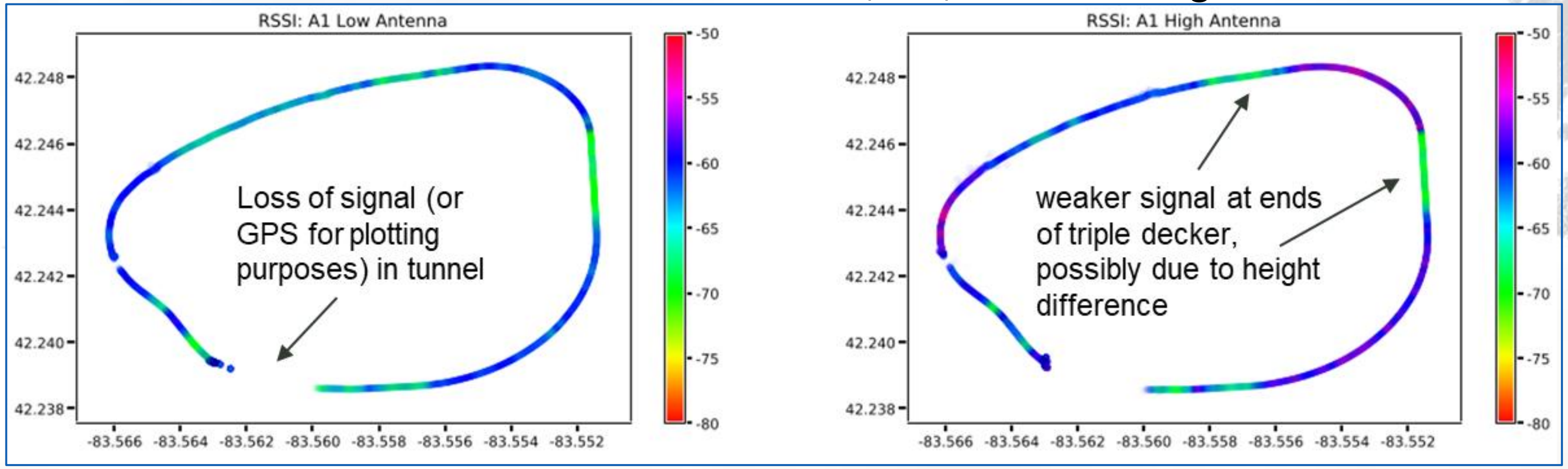
- All KPIs in baseline conditions are significantly better than target for vehicle-to-vehicle (V2V) requirements
- Dropped packets <0.1% (estimate; message rate 10Hz)

Project Progress & Accomplishments:

Example V2V Communication Testing

- Two antenna positions investigated:
  - Low (side view mirror)
  - High (roof of cab)
- Principle challenges are structures, e.g. tunnels, overpasses
- Higher antenna on Lead truck results in ~3 dBm higher RSSI

Low Lead Truck (100’) High

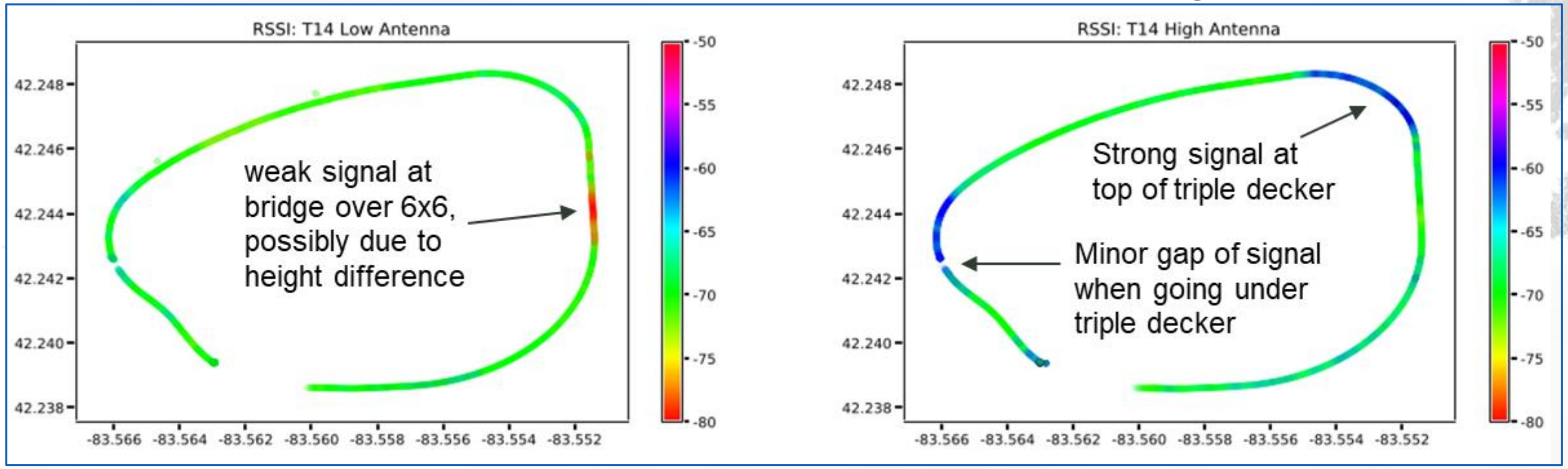


A1_Low	RSSI dBm	Latency ms		A1_High	RSSI dBm	Latency ms
Mean	-63	2.55		Mean	-60	2.53
Std Dev	5	0.85		Std Dev	7	0.86
Min	-86	1.49		Min	-87	1.51
Max	-50	70.95		Max	-42	19.30

Example V2V Communication Testing

- Follower (middle) truck also improves ~4 dBm RSSI
- (Ref. 3 dBm increase yields 2x power and √2x (41% more) range)

Low — Middle Truck (100’) — High

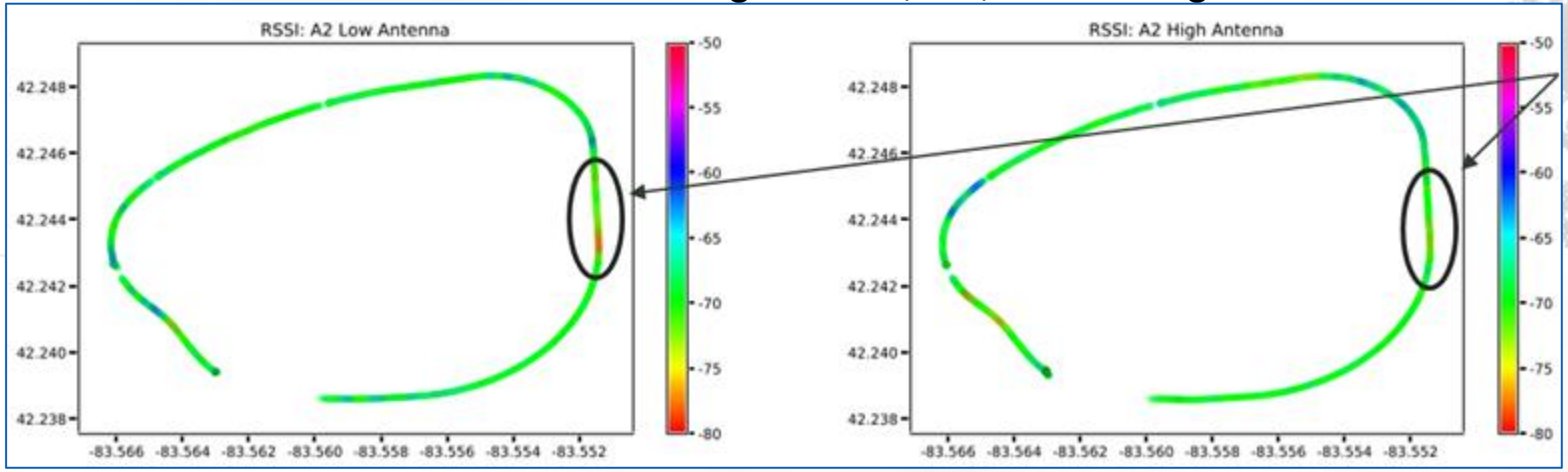


T14_Low	RSSI dBm	Latency ms		T14_High	RSSI dBm	Latency ms
Mean	-70	2.55		Mean	-66	2.55
Std Dev	7	0.79		Std Dev	7	0.78
Min	-90	1.57		Min	-97	1.51
Max	-51	70.94		Max	-44	19.25

Example V2V Communication Testing

- Trailing truck mean RSSI did not improve
- RSSI consistency (Std Dev) improved from 6 to 5

Low Trailing Truck (100') High

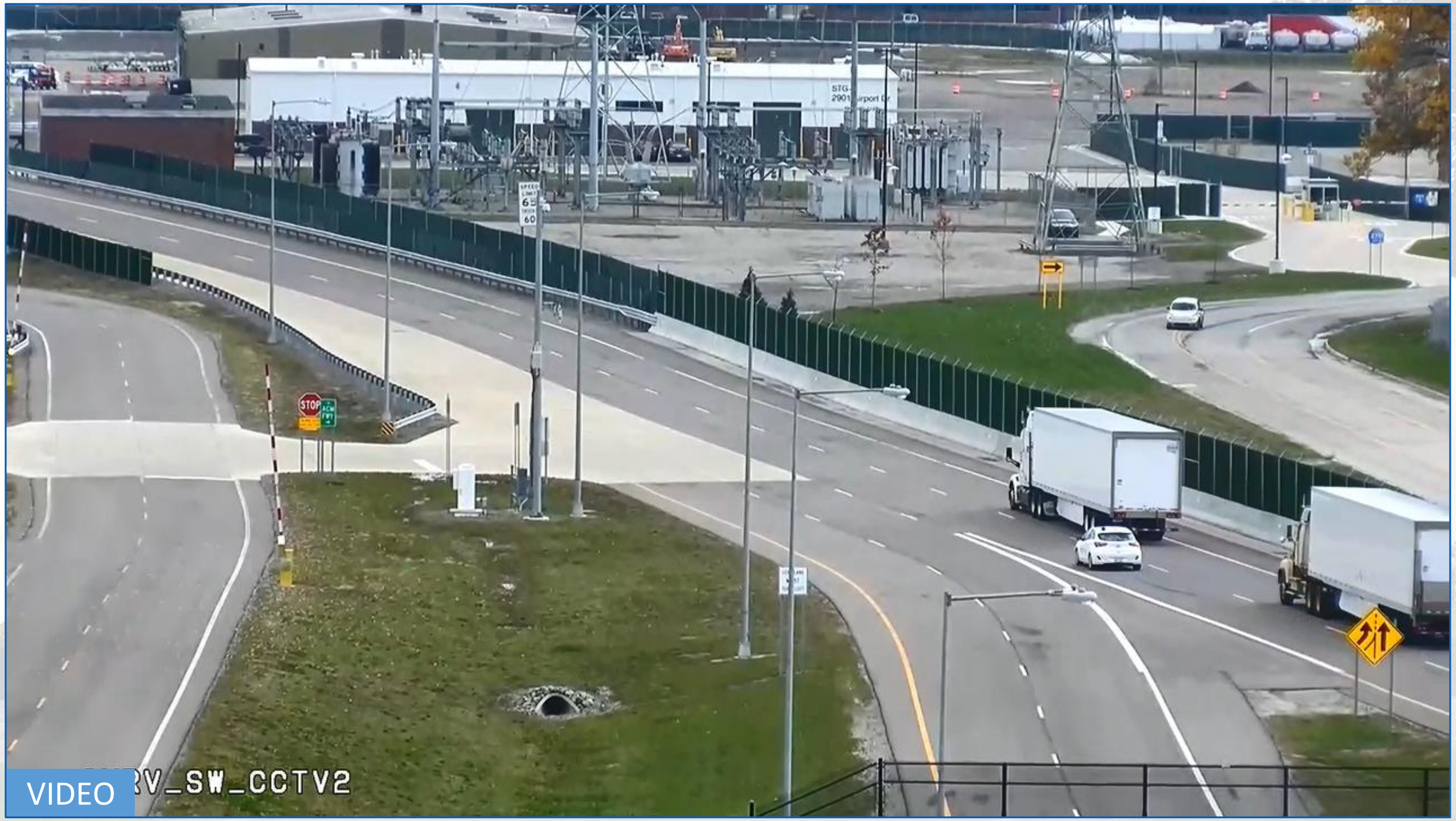


A2_Low	RSSI dBm	Latency ms		A2_High	RSSI dBm	Latency ms
Mean	-69	2.57		Mean	-69	2.55
Std Dev	6	1.02		Std Dev	5	0.87
Min	-91	1.52		Min	-88	1.39
Max	-50	100.92		Max	-51	20.68

Example Traffic Challenge

Cut-In / Merge

- Reform 4-truck platoon vs continue separately afterwards?
  - Which provides greater overall fuel savings?
- An energy analysis of cut-ins and merges, coupled with two- and four-truck platoon results will inform this decision



Simulation – Impact of Weather

<u>What If?</u>

Target: 2 second headway time

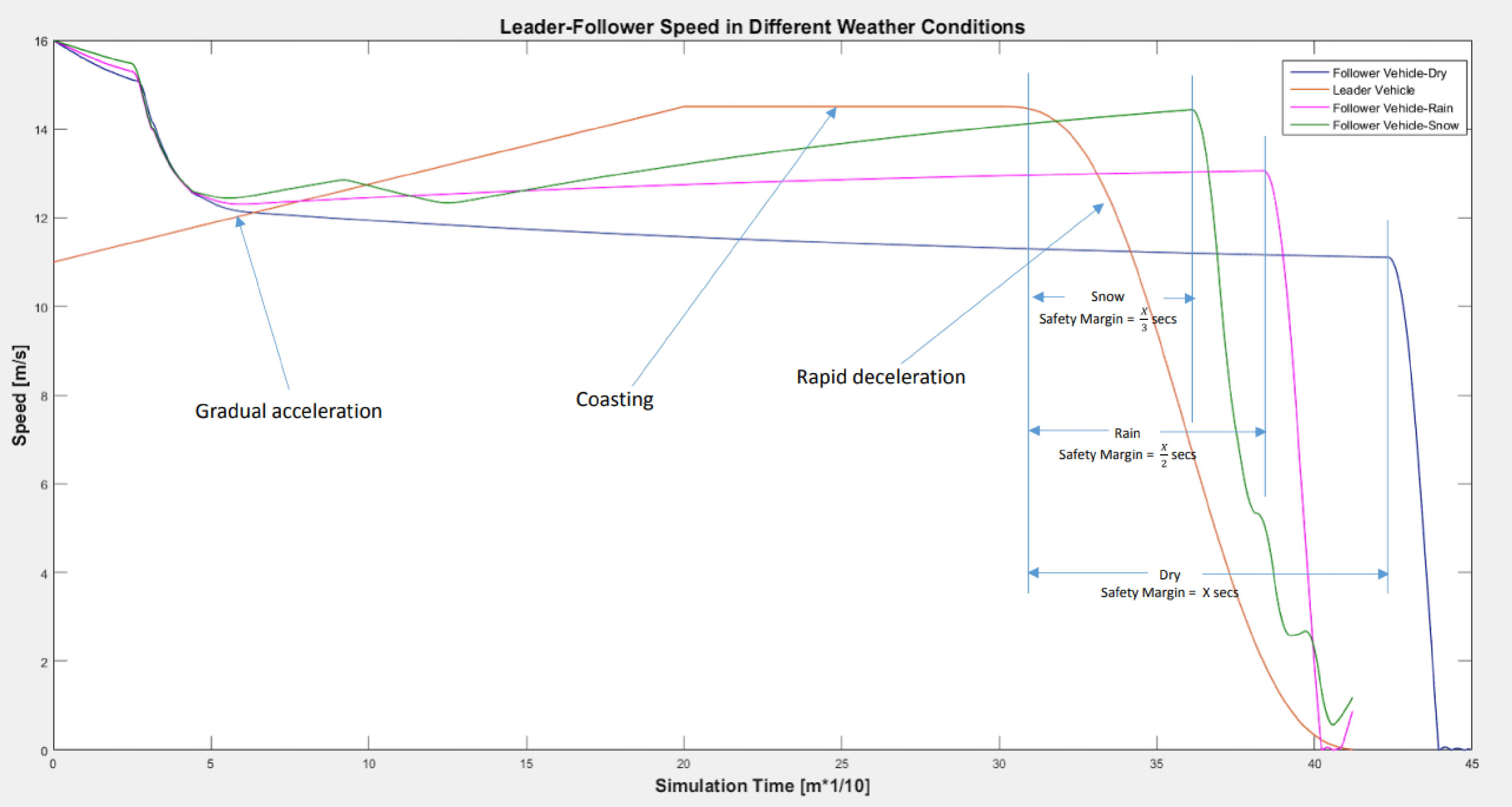
<u>Performance*</u>

- Rain – Safety margin reduced 50% vs dry
- Snow – Safety margin reduced 67% vs dry weather

*(Braking, radar, and V2V degradation)

<u>Effect</u>

Equivalent safety margin can be achieved with increased headway time (distance), but impacts fuel savings opportunity



Project Progress & Accomplishments:

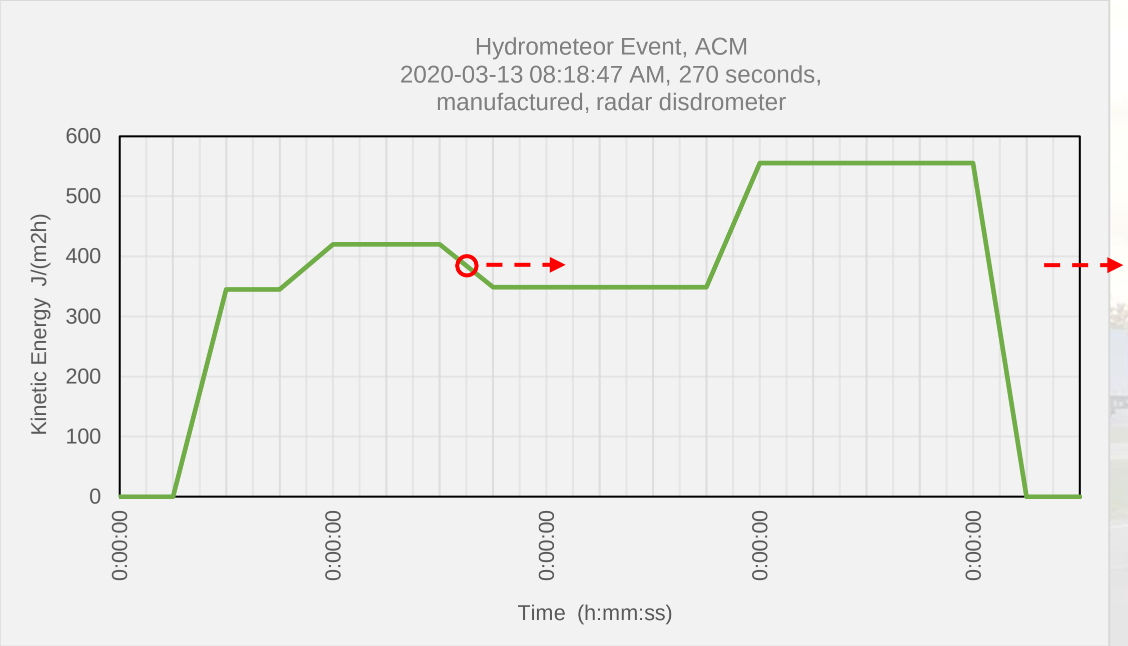
Weather measurement

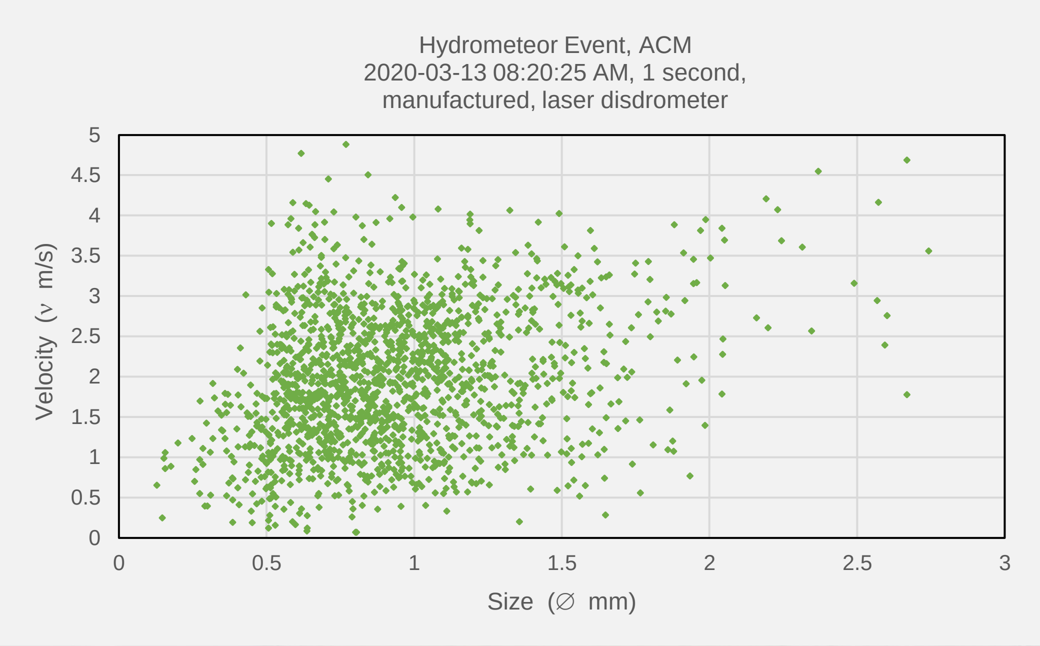
- Rain events have a ‘fingerprint’:
  - Develop objective measures:
    - Drop size & distribution
    - Drop velocity & distribution
    - Kinetic energy
  - Instruments – disdrometers:
    - Laser, optical, radar
  - Generate repeatable artificial rain
- Static weather stations are limited:
  - Better – measure directly on vehicle (radar)
- Weather model validation
  - Compare real, artificial, and simulated rain
  - Also applies to snow, sleet, etc.

Example Objective Rain Characterization

- Rain events have a ‘fingerprint’:
  - Develop objective measures:
    - Drop size & distribution
    - Drop velocity & distribution
    - Kinetic energy

Particle Size (∅ mm)	Particle Velocity (ν m/s)	Sample
1639	1639	Size
0.974	1.976	Mean
0.882	1.916	Median
0.509	0.896	Std Dev





Team Collaboration & Coordination

Partners

American Center for Mobility

PI, PM, & Test Facility

Auburn University

Automation, Localization, Vehicles & Testing

Michigan Dearborn

V2V Communications

Specialized Support

DEVCOM Ground Vehicle Systems Center

Vehicles

NREL Transforming ENERGY

Data Acquisition

MDOT

Public Infrastructure

*National Energy Technology Laboratory

Team Collaboration & Coordination

Partners

American Center for Mobility	Auburn University	UM Dearborn
PI & Test Facility	Automation, Localization, Vehicles & Testing	V2V Communications

Specialized Support

DEVCOM Ground Vehicle Systems Center	NREL Transforming ENERGY	MDOT
Vehicles	Data Acquisition	Public Infrastructure

- Most team members have worked together on prior and related projects
- Complimentary skillsets
- Quad Chart-structured coordination
  - Progress, Goals, Lessons, Help Needed

- Team collocation during testing at NCAT and ACM
- UM-D faculty collocation at Auburn during summers
- Regular meetings/visits with NETL* PM

**National Energy Technology Laboratory*

Market Impact and Sustainability

Achievements to Date

- Reduced fuel consumption during 4-truck platooning (45mph, unloaded, mixed platoon)
  - 5-10% for following vehicles
  - 0-4% for the leading vehicle
- Automation algorithms demonstrated ability to lengthen headway gap for cut-in traffic
- V2V communications shown resilient to vertical road curvature, bridges, tunnels, and weather

Future

- Develop algorithm performance further in 2nd round of Baseline and Advanced testing at NCAT and ACM
- Conduct public road demonstration
- Publish findings and best practices – sharing with entities commercializing platooning technology
- Address lack of talent in Connected & Automated Vehicle (CAV) talent pipeline – 13 degree candidates participating in project:
  - 3 BS, 7 MS, 3 PhD

Summary

Objectives	Approach	Accomplishments	Future
• Develop vehicle automation for reduced headway that adapts to: ◦ Traffic (gap for cut-ins) ◦ Road curvature (vertical and lateral) ◦ Bridges and Tunnels ◦ Weather (vehicle dynamics & communications) • Conduct testing with increasing complexity in four phases: Simulation, Baseline, Advanced, Public	• Test vehicles in varying automated platoon configurations • Measure fuel consumption • Increase the complexity of driving scenarios	• Reduced fuel consumption during 4-truck platooning ◦ 5-10% - following vehicles ◦ 0-4% - leading vehicle • Automation algorithms demonstrated ability to lengthen headway gap for cut-in traffic • V2V communications shown resilient to vertical road curvature, bridges, tunnels, and weather	• Develop algorithm performance further in 2nd round • Conduct public road demonstration • Publish findings and best practices • Add talent to CAV workforce: 13 degree candidates participating in project

Technical Backup Slides

Example Fuel Consumption Testing

Data By Lap

- CAN Fuel Rate
  - Good agreement with gravimetric data
  - Show general fuel consumption trends
- Outlier laps easily removed
  - Isolate disturbances from fuel consumption results